Planning for Planetary Protection: Challenges Beyond Mars

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Abstract— In situ analysis for targets beyond Mars brings new challenges in planetary protection, where planetary protection preserves the chemical environment of a target body for future life-detection exploration and, in sample return missions, protects the Earth from potential extraterrestrial contamination. The NASA Solar System Exploration Program roadmap calls for missions to bodies of interest for life-detection or prebiotic science, including Europa, Titan, and comets. These targets present challenges because NASA planetary protection policies specify new requirements for missions to Europa, and new guidelines for Titan are anticipated; furthermore, the comet missions have additional significance because they are envisioned to be sample return missions. This document summarizes the technical challenges to planetary protection for these targets of interest and outlines some of the considerations, particularly at the system level, in designing an appropriate technology investment strategy for targets beyond Mars.

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1. INTRODUCTION

Planetary protection is defined as the regulations imposed on robotic space missions to prevent biological contamination of future exploration sites and, in sample return missions, to protect the Earth from extraterrestrial contaminants. Historically, while the Viking mission satisfied stringent planetary protection requirements, the negative results from Viking's life-detection experiments led to less stringent planetary protection measures on subsequent missions.

However, a number of scientific advances have reversed this trend. Increased understanding of the breadth of microbial extremophilia [1] led to renewed interest in survivability in a number of environments previously seen as uninhabitable. In 1996, McKay et al. published new images and analysis of the Mars-originated ALH84001 meteorite [2]; its features and mineralogy sparked renewed interest in astrobiology. In more recent years, results returned from the Mars Pathfinder and Mars Exploration Rover missions further enhanced the understanding of the hydrogeological history on Mars and the likelihood that water once existed on the surface [3], prompting a revised view of the survivability on Mars.

New data were obtained from other targets, as well. The Galileo mission to the Jovian environment returned images and data suggesting that above the metallic core of the icy moon, Europa, lies a water ice-liquid shell of total thickness 80-170 km [4,5]. More recently, the Cassini orbiter and the associated Huygens probe have returned data on Saturn's moon, Titan [6], showing the complex hydrogeology of a landscape strongly affected by organic chemistry.

NASA's ongoing interest in astrobiology has led to the development of a roadmap for Solar System Exploration to further characterize these targets with environments of interest to astrobiology. However, the potentially habitable nature of these targets, including Mars, has led to the development of a more stringent set of requirements [7] for relevant missions, and further developments and revisions are not excluded.

It is anticipated that to meet these requirements, an integrated technology development strategy will be necessary. In addition, because the contamination risk is, by nature, not a localized phenomenon for some of these targets, many of the technology solutions will be required to address contamination at the system level, rather than simply with additional component development. Systems engineering will therefore need to be integrated with planetary protection at the earliest mission design phases. This document highlights some of the key planetary protection concerns for exploration of targets other than Mars and suggests avenues for technology research and development.

2. FUTURE MARS EXPLORATION

Buxbaum [8] provides a complete history of the Mars Program and its approach to satisfying planetary protection requirements. The missions to Mars planned for the near-term include Phoenix, scheduled for launch in September 2007, and the Mars Science Laboratory (MSL) mission, slated to launch in 2009.

The Phoenix mission, intended to land in the northern polar cap, would sample the icy soil below the surface. As a result, the sample acquisition system will likely satisfy more stringent planetary protection requirements. To do so, it is planned that the sampling system, once sterilized, will be enclosed and isolated during the assembly, test, and launch operations (ATLO) processes.

MSL is envisioned to be equipped to detect low levels of organic materials but will not have life-detection capabilities. Like the Mars Pathfinder and Mars Exploration Rovers, MSL will likely take advantage of High Efficiency Particle Arrestor (HEPA) filters to isolate enclosed regions of the spacecraft and prevent contamination of the vicinity of the landing site.

On a longer time scale, the Mars Sample Return mission, recently deferred, is envisioned to be the first robotic sample return mission facing substantial back contamination requirements. These requirements are designed to prevent contamination of Earth by extraterrestrial biological material, as well as limit the probability of terrestrial organisms making a so-called "round-trip". As a result, the entire mission, and particularly the sample handling and containment system, would be subject to stringent forward contamination control.

3. EXPLORATION BEYOND MARS

NASA's current Solar System Exploration roadmap is shown in Figure 1 and describes a proposed sequence of missions. Mission concepts with science objectives related to astrobiology include missions to the Europa, Titan, and two comet sample return missions.

Two missions to the Jovian moon Europa are in the planning stages: Europa Geophysical Observer (EGO) and Europa Astrobiological Lander (EAL). While EGO, with a launch date as early as 2013, is designed as an orbiter mission, it is possible that a small landed package could conduct preliminary in situ science. EAL is envisioned as a follow-on mission equipped with complete in situ analysis capabilities, with a launch date late in the second decade.

The Solar System Exploration roadmap further calls for a mission to Titan, the Titan Explorer, early in the second decade. Architecture variants on this mission include the possible use of an orbiter, particularly to facilitate telecommunications. The Titan Explorer would likely include an aerial platform to conduct in situ investigations; this aerobot may have the capability to collect samples for analysis.

Finally, the Solar System Exploration roadmap also describes returned sample mission concepts in the form of the Comet Surface Sample Return (CSSR), with a planned launch date of 2013, and the Comet Cryogenic Sample Return (CCSR) mission, with a launch date in the second decade. These missions are envisioned to sample the surface and the subsurface (at 10 m depth), respectively, of comets potentially rich in organic materials. They would further conduct limited in situ analysis to provide a context for the returned sample analysis.

Each of these target environments poses unique challenges to the compliance of planetary protection requirements and contamination control. Many of these topics have been identified in NASA planning activities [9]. The following sections describe issues specific to each environment and general principles underlying appropriate contamination control measures.

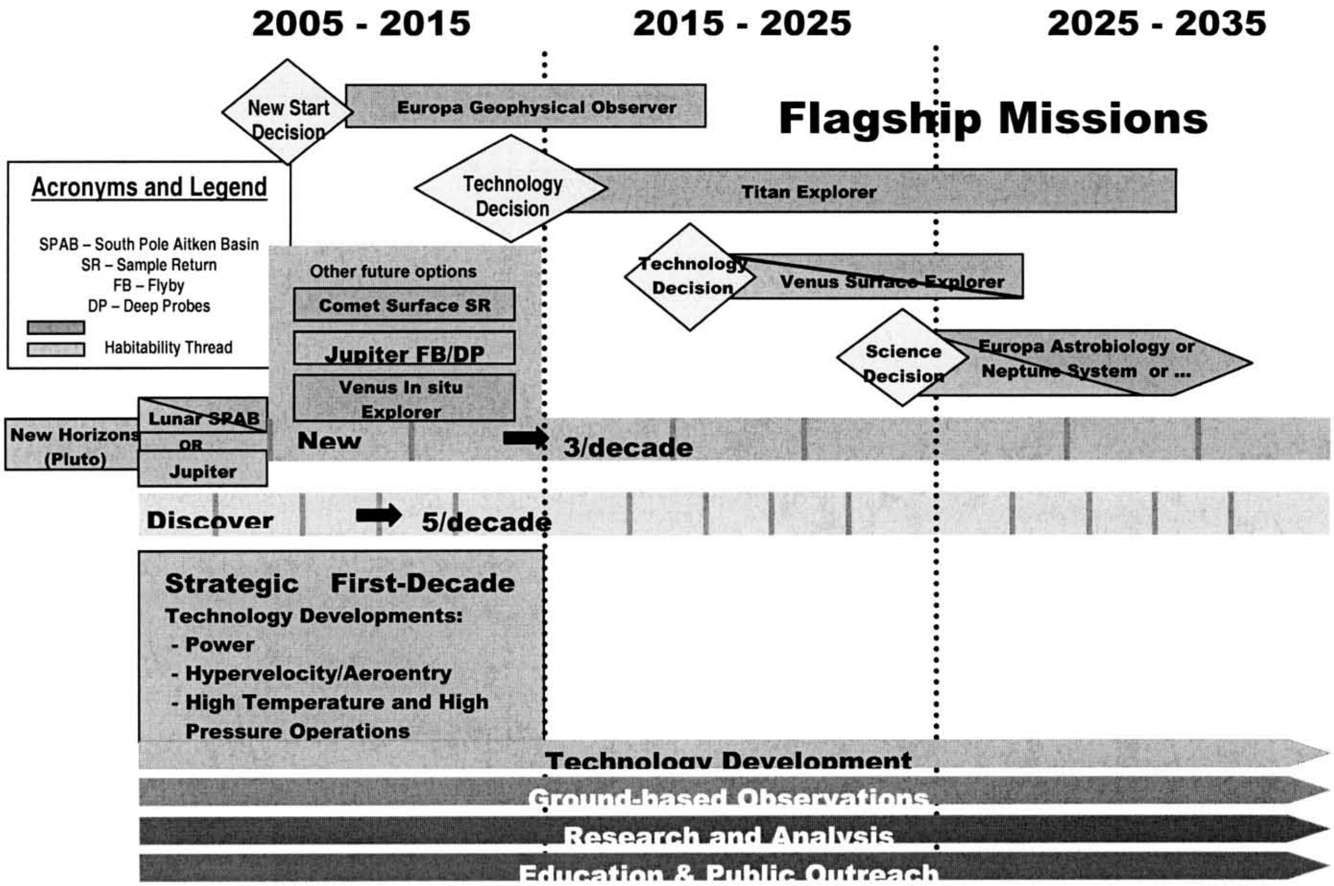

Figure 1. The Solar System Exploration Roadmap.

4. Europa

Missions to Europa present a number of technical challenges even before the consideration of planetary protection. The technical challenges posed by these missions can be summarized in three general characteristics: a) The ambient environment, b) the absence of an atmosphere, and c) the global ocean. This section will briefly describe these factors and how they might interact with satisfying the requirement that the probability of contamination of the global ocean be less than 1×10^{-4} [7].

a. The ambient environment

The environment surrounding Jupiter has an unusually strong magnetic field; in addition, it appears that this field has a strong quadrupole moment, giving it an unusual spatial shape. As a result of this field, particles ejected by the solar wind, such as electrons and protons, may be captured by this strong field and given additional energy. This phenomenon produces a strong radiation field around Jupiter. In addition to the energetic light particles, heavier ions have also been measured; it is possible that this flux is related to volcanic eruptions from Io.

The Galileo data have been used to develop a new model with better spatial, temporal, and spectral fidelity [10]. The radiation environment at Jupiter is dominated by electrons ranging up to 500 MeV in energy, with some proton flux up to approximately 20 MeV. In contrast, the Earth's Van Allen belts are dominated by protons of only 100 MeV maximum energy, with electrons showing very little strength after 7 MeV. Because our general understanding of the impact of radiation on electronics is driven by experience near Earth, we have not yet developed the capability to fully understand the implications of the radiation and subsequently protect against such high fluxes and high energies of incident electrons.

Therefore, orbiter missions in the Jovian environment will, at a minimum, require shielding to provide protection from the ambient radiation; dosages may reach 40 krad/day in an orbiter and 20 krad/day on the surface (assuming that the satellite itself provides shielding for half the time).

However, in situ experiments on the surface of Europa are likely to require additional technology development for radiation tolerance in components such as electronics and packaging, as well as in actuators and other electromechanical systems needed for sample acquisition capabilities. This challenge is compounded by the ambient surface temperature of -180°C, requiring further development for technologies such as batteries.

Given the breadth of technical challenges presented by a mission to the low-temperature, high-radiation environment on Europa, it is not surprising that planetary protection requires added consideration from the earliest design stages. Currently, the only bioburden reduction technique approved by NASA is dry heat microbial reduction (DHMR). This procedure, developed in the 1960's for the Viking project, exposes subsystems or assembled systems to elevated temperatures (approximately 125°C) for durations varying with the exposure of the surface to the ambient environment. It is anticipated that this process may affect the performance of electronics and packaging materials developed in recent years. While these issues appear at a limited level for an orbiter mission, where it is presumably easier to protect some subsystems from the ambient radiation and low temperature, a landed package will be able to take advantage of these same isolation techniques. Therefore, a lander will likely require development of new components and subsystems; these elements would require further study for compatibility with sterilization techniques.

While alternative sterilization modality are currently under study, it is worth noting that compatibility studies will be necessary for any combination of a novel material and a sterilization techique. It is further critical to infuse these considerations into the ATLO flow in order to prevent recontamination of a sterilized component or subsystem.

A separate set of issues exists for the microbial tolerance to the ambient environment. In principle, it is possible that radiation-tolerant terrestrial organisms may thrive for a limited time in this environment; however, this effect would likely wane with the increased duration of exposure. The survivability may also vary with the other environmental factors; i.e., results from microbiolgy experiments conducted with rich media may not be applicable to the dessicated environment, likely to be poor in most nutrients.

On the other hand, it may be possible to exploit the maleficent nature of this environment as a terminal sterlization step. To do so, an experimental plan would have to identify likely contaminant organisms present during ATLO, then expose them to a environment simulating the Jovian conditions with reasonable assumptions for nutrient concentrations. This simulated environment would, by necessity, differ somewhat from radiation environments often studied in microbiology research; i.e., simulants of the appropriate fluxes and energies would be necessary. This set of microbiology experiments would possibly lead to a cost-effective sterlization modality during deep space cruise or mission operations. Such a plan, however, would require the additional caveat that some of the biological material might remain in place even under lethal conditions, possibly leading to a false positive in a life-detection experiment. To understand this effect, it would be necessary to determine the fate of the biological materials upon delivery of the letal doses to look for volatilization or other mechanisms for loss of biological material.

b) The absence of an atmosphere

An additional factor in planetary protection planning for missions to Europa is the absence of an atmosphere. The Mars atmosphere was used to successfully mitigate contamination risk in the case of the Mars Reconnaisance Orbiter; the mission's eccentric orbit limits the orbital lifetime to values lower than those allowed by the planetary protection requirements. However, an analysis showed that the heat fluxes experienced during atmospheric entry were sufficient to sterilize the exposed and mated surfaces [11]. Such a contamination reduction technique is not available to orbiters about Europa, where atmospheric entry will not take place.

In further contrast to missions to Mars, the absence of an atmosphere requires a propulsive landing system. Such a system may distribute propellant in the immediate vicinity of the landing site, posing additional contamination risk. For missions to Mars, technology development has advanced in so-called "covered sampling" tools, used to mitigate local surface contamination to expose a clean sample. However, the development to date has been directed toward tools able to scrape into the Mars subsurface and have not been developed for ice. While extensions to these tools from the Mars surface to ice may certainly be feasible, the technology will still require further development. The propellant distribution and sterilization properties will still require further analysis because of the global ocean, described below.

c) The global ocean

Galileo data suggested that the surface of Europa is characterized by a layered liquid-water ocean covered by an icy crust [4,5]. This discovery led to an initial methodology proposed by the National Research Council to assess the probability of contamination of the ocean [12]. This risk of global contamination of the ocean via a conduit to a locally contaminated site on the icy surface is limited by NASA policy to 1×10^{-4} [8]. The first application of this methodology to a mission concept was undertaken by the Jupiter Icy Moons Orbiter project [13], now terminated. However, the underlying analysis is still relevant to future missions in the planning stages.

This contamination probability is not trivial to analyze because of the wide disparity in models describing the satellite's core processes, ice mechanics, and origins of the surface topography [13, and references therein]. These models are relevant to planetary protection because they suggest values for the timescale on which contamination transport from the surface to the ocean takes place. Outer limits on these timescales may be constructed from surface ages estimated by analysis of cratering rates; the age of the surface of Europa is currently estimated to be approximately 60 million years [14]. These results suggest that in that time, any site with local contamination will reach the global ocean.

The breadth of models describing the various dynamics provides one set of motivations for a dedicated mission to Europa. However, the variation in these models will likely drive the precision of the estimates for the contamination transport timescale. An approximate determination of this timescale is key to planetary protection because the requirements are expressed as integrated probabilities per mission rather than annualized values. Therefore, refining and integrating the various models for the dynamics of the Europa surface will be important because analysis of many of these processes gives rates for reaching the ocean from the surface; these rates must be integrated in order to provide a probability per mission.

The icy crust on the ocean also leads to other considerations in spacecraft design. For instance, the Mars Phoenix lander, scheduled for launch in 2007, has plans to implement a biobarrier around a sterilized sampling arm to prevent recontamination during the ATLO process. This choice of architecture assumes that the arm is the only element of the spacecraft that will potentially contaminate a local site. Such an architecture choice is not available for a lander on Europa, because any element will ultimately be in contact with the ocean at the end of a resurfacing cycle.

5. TITAN

The primary planetary protection considerations for a mission to Titan are centered on two observations: a) The organic materials in the surface and the atmosphere; and b) the mission architecture. Although the requirements for missions to Titan have not yet been defined, it is anticipated that the requirements will be stringent in order to protect the integrity of the returned science. Under that assumption, it is possible to understand the general concerns associated with such a mission.

a. The organic materials.

The Titan surface and atmosphere present signatures consistent with organic materials, making this a target of interest for investigations in prebiotic chemistry. On Titan, microbial survivability faces more challenges because of the low solubility of biomaterials in the surface solvents; however, this does not obviate the possibility of life [15]. As a practical matter, though, this poses new challenges for biomarker detection, unlike Mars, where life detection has largely been based on the detection of organic materials in an organic-poor environment. This change in paradigm affects both the in situ instrument design and the necessary supporting microbial survivability experiments.

Like missions to Europa, missions to Titan would require an experimental strategy that begins with the contaminants likely to survive ATLO and propagates them through a relevant environment. If pursued early enough, such a set of experiments would probably influence the in situ instrument design and may even shed light on the underlying mechanisms that would promote survivability in the organic environment on the surface of Titan.

b. The mission architecture.

Because Titan's atmosphere has a surface pressure 50% higher than that of Earth and with signatures indicative of photochemical processes, a balloon architecture is appealing to directly measure atmospheric properties. In particular, an aerial vehicle with sample acquisition capabilities would be able to address a wide range of scientific questions. Such a vehicle, however, would be subject to the same constraints as that of a lander on Europa; that is, the atmosphere would presumably serve as a conduit for global contamination. This further suggests that a biobarrier architecture protecting an isolated part of the spacecraft, like that on the Mars Phoenix mission, would not be a suitable option. It is further likely that the balloon materials and aerobot architecture would likely be subject to stringent cleanliness requirements.

An added challenge is the ambient temperature; like Europa, the surface temperature on Titan is approximately -180°C. Therefore, the components and batteries associated with in situ exploration will need to be designed for tolerance to low temperatures, particularly for sample acquisition systems exposed to the environment. It is anticipated that extensive sterilization compatibility studies will be necessary for low-temperature components.

6. COMETS

Because of the uninhabitable nature of comets, as targets they do not pose pose significant challenges to forward contamination control technologies. However, two missions envisioned for comet studies would call for sample return capabilities; namely, the Comet Surface Sample Return and the Comet Cryogenic Sample Return missions. While these missions are not anticipated to have forward contamination requirements as strong as those for Mars, Europa, and Titan, containment measures for the returned sample are still envisioned to be strict and will therefore interact with the sample acquisition system.

Like MSR, sample return for these missions implies that a sample containment system will require attention. Break-the-chain refers to the process of breaking the chain of contact between the returned sample vehicle and the target's surface. This process includes container sealing and leak detection, as well as mitigation measures for the outside of the returned sample vehicle. While it is anticipated that the sample containment system would build on the technologies developed by MSR, additional development would be needed for samples that are primarily icy in character rather than dehydrated, particularly for mitigation measures because the MSR architecture was designed to mitigate against dust, rather than ice, contamination.

Table 1. Summary of major challenges to planetary protection and contamination control for targets other than Mars.

Target	Factor	Consequences
Europa	Low temperatures	• Sterilization compatibility of low temperature components
	Radiation	• Sterilization compatibility of radiation hard components • Microbial survivability mechanisms unclear • Possible use of radiation as terminal sterilization step
	Absence of atmosphere	• Possible site contamination by propellant • Unsuitability of atmospheric entry as sterilization technique
	Nature of icy crust/global ocean	• Rates of contaminant transport from to the ocean • Unsuitability of biobarriers to isolate selected landed elements from global ocean
Titan	Low temperatures	• Sterilization compatibility of low temperature components
	Organic matrix	• Microbial survivability mechanisms unclear • Biobarker detection techniques unclear
	Atmosphere	• Sterilization compatibility with aerial vehicle components
Comets	Ice	• Design of returned sample containment system • Break-the-chain strategies

7. CONCLUSIONS

A number of mission concepts to bodies beyond Mars call for the capability to conduct in situ experiments related to astrobiology. However, pursuing life-detection experiments or studies in prebiotic science brings the parallel challenge of meeting existing or anticipated planetary protection requirements, as well as the stringent contamination control measures needed to preserve the integrity of the returned science. To bring these mission concepts to maturity, it will be necessary to fully understand the many ramifications of planetary protection on mission design aspects ranging from trajectory design to component selection and subsystem integration. These various mission elements will require integration with results from fundamental microbiology survivability experiments and associated planetary protection technology development, therefore calling for a systems engineering approach to addressing these factors at the earliest stages of mission design. Ultimately, an integrated technology development strategy will be necessary to address the breadth of technology development and integration needs.

REFERENCES

[1] K.H. Nealson, "Post-Viking Microbiology: New Approaches, New Data, New Insights", Origins of Life and Evolution of the Biosphere 29, 73-93, January 1999.

[2] D.S. McKay, et al., "Search for Past Life on Mars: Possible Relic Biogenic Activity in Martian Meteorite ALH84001", Science 273, 924-930, August 16, 1996.

[3] S. W. Squyres, et al., "In situ Evidence for an Ancient Aqueous Environment at Meridiani Planum, Mars", Science 306, 1698-1703, December 3, 2004.

[4] M.H. Carr, et al., "Evidence for a Subsurface Ocean on

Europa", Nature 391, 363-365, xxx 1998.

[5] J.D. Anderson, et al., "Europa's Differentiated Internal Structure: Inferences from Four Galileo Encounters", Science 281, 2019-2022, xxx 1998.

[6] C. Elachi, et al., "Cassini Radar Views the Surface of Titan", Science 308, 970-974, May 13, 2005.

[7] NASA Procedural Requirements 8020.12C, Effective Date April 27, 2005.

[8] A. Belz, et al., "Planetary Protection and Contamination Control Technologies for Future Space Science Missions", JPL D-31974, 2005.

[9] K. Buxbaum, "Planetary Protection Technologies: Technical Challenges for Mars Exploration", IEEE Aerospace Applications Conference Proceedings, 2005.

[10] J. F. Cooper, et al., "Energetic Ion and Electron Irradiation of the Icy Galilean Satellites", Icarus 149, 133-159, 2001, doi:10.1006/icar.2000.6498.

[11] J. Witte, et al., "Taking Entry Heating Credit to Address Planetary Protection Bio-burden Limits", 35th COSPAR Scientific Assembly, 18 - 25 July 2004.

[12] L. Esposito, and Members of the Task Group on the Forward Contamination of Europa of the Space Studies Board, "Prevening the Forward Contamination of Europa", Washington, D.C.: National Academy Press, 2000.

[13] R. Gershman, C. Kohlhase, R. Koukol, "Planetary protection for the Jupiter Icy Moons Orbiter", 35th COSPAR Scientific Assembly, 18 - 25 July 2004, and references therein.

[14] K. Zahnle, et al., "Cratering Rates in the Outer Solar System", Icarus 163, 263-289, 2003.

[15] C. P. McKay and H. D. Smith, "Possibilities for Methanogenic Life in Liquid Methane on the Surface of Titan." Icarus 178, 274-276, 2003.

BIOGRAPHY

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